Disentangling entanglement

Antony R. Crofts

Department of Biochemistry and Center for Biophysics and Computational Biology
University of Illinois at Urbana-Champaign, Urbana IL 61801

Correspondence:
A.R. Crofts
Department of Biochemistry
University of Illinois at Urbana-Champaign
419 Roger Adams Lab
600 S. Mathews Ave

Phone: (217) 333-2043
Fax: (217) 244-6615
Email: a-crofts@life.uiuc.edu
Introduction

Since the birth of quantum mechanics (QM) with Planck’s explanation for the ultraviolet catastrophe through a Boltzmann treatment of discrete states, and de Broglie’s suggestion that objects of mass in the quantum range should show detectable wavelike properties, these two strands have led to the idea that quantum objects sometimes behave like particles and sometimes like waves. The problems raised by that “particle/wave duality” have remained at the core of philosophical discussions of quantum mechanics, and interpretations have been extended as our knowledge has expanded. Because of the difficulties pointed out by Heisenberg, the behavior in the wave-like regime cannot be measured without uncertainty, and, although some properties of this domain can be assayed, it is only through interactions in the particle-like domain. These properties introduce both epistemological and ontological problems, and have resulted in an extensive literature that sometimes appears to the outsider as arcane.

The EPR paradox

In his argument with Bohr in the mid 1930s on what is now known as the EPR paradox (see the Einstein-Podolsky-Rosen paper [1]), Einstein was concerned about the apparent contradictions between the “spooky actions at a distance” (non-locality) implied by quantum mechanical interpretations of correlations between quantum entities (“entanglement”), and the limitation on energy flux to the speed of light implicit in special relativity (locality). The problem was that the quantum mechanical treatment required a description in terms of a wavefunction encompassing two or more quantum objects that extended through space to arbitrary distance, and which appeared to predict the outcome of separate measurements on the objects. The measurement of one object, in terms of properties (location, orientation, spin) that reflect the energy content of the system, seemed to determine similar but complementary properties of another remote state. For entangled states, this seemed to imply that the state of a distant physical entity would be determined by the properties of an entangled partner measured locally, which seemed to require that energy be exchanged faster than light. Either relativity was wrong, or quantum mechanics did not provide a complete description (in a deterministic sense) of what was happening (in the physical sense) during the temporal evolution of the “entangled” states. As Fine has noted [2], Einstein later summarized his position in a letter to Max Born [3], as follows:

“…the paradox forces us to relinquish one of the following two assertions:

(1) the description by means of the \( \psi \)-function is complete

(2) the real states of spatially separate objects are independent of each other.”

The ambiguities explored in [1] were extended to complementary spin states by Bohm [4, 5], received a seminal restatement by Bell [6], and have engendered a continuing discussion on entanglement, coherence, and collapse of the wavefunction. The coherence of entangled states, the collapse of the wavefunction, and the “actions at a distance” seen in entanglement experiments, seemed in some interpretations to imply that something moves faster than light, but whether that is so, and what that “something” is, have become matters of contention.

The philosophical background
In the standard “Copenhagen interpretation” of Bohr and Heisenberg [7-9], the ambiguities were dealt with in the context of a prevailing philosophical view, influenced perhaps by the arguments between the “atomists” and “energists” [10], and Boltzmann’s ideas on the centrality of measurement as the epistemological underpinning of hypothesis. Since measurement provided the link between the quantum mechanical and a classical physical interpretation, a complete treatment was taken as demanding a formal description of the evolution between states accessible to measurement. The initiating and final states were accessible to measurement, but the evolving wave-like state was not, so the treatment was thought to require a wavefunction that encompassed the evolution from the initiating transition. In the case of entangled entities, this required a common wavefunction that therefore “evolved” in the intervening space as the particles separated. The wavefunction was claimed to provide a “complete description”, but it was unclear what was meant by this. The Schrödinger equation was developed in the context of a time-independent treatment of electron energy levels in the H-atom, made realistic because of the standing-wave constraint, but the terms, although they contain classical energy functions, are modified by the $\psi$-function so as to represent probabilities. The same is true of the evolving functions used to describe the entangled entities, but the presence of energy terms had been taken to imply a more causal description that embraced a thermodynamic status.

Although Bohr is usually represented as championing the view that quantum theory provided a complete description, what he advocated was more subtle [8]:

“The entire formalism is to be considered as a tool for deriving predictions, of definite or statistical character, as regards information obtainable under experimental conditions described in classical terms and specified by means of parameters entering into the algebraic or differential equations of which the matrices or the wave-functions, respectively, are solutions. These symbols themselves, as is indicated already by the use of imaginary numbers, are not susceptible to pictorial interpretation; and even derived real functions like densities and currents are only to be regarded as expressing the probabilities for the occurrence of individual events observable under well-defined experimental conditions.”

In the words of Jeffrey Bub “…the import of the state then lies in the probabilities that can be inferred (in terms of the theory) for the outcomes of possible future observations on the system” [11].

An alternative approach was that of David Bohm [12, 13] (reviewed and extended in a philosophical context by Goldstein [14]). Bohmian dynamics defines the evolution of the physical configuration (the particle velocity) in terms of the quantum probability current/density, so that the evolution of the wave function described by the Schrödinger equation has a “guiding” role for the particle. In Bohmian dynamics, the explanatory power of classical quantum dynamics is retained, but the wavefunction has a less ambiguous status, - the trajectory of a locally constrained quantum object appears to be directed by the probability function through a quantum potential field. This treatment has the advantage of avoiding the difficulties of the collapse of the wavefunction; - in informal terms, the quantum object always has its particle-like nature, but only goes where the wavefunction “says” it can. However, the wavefunction appears to have a more causal role.

The paradoxical properties of entangled states have generated extensive speculation about their philosophical and mechanistic status. For example, a comprehensive discussion by Abner Shimony [15] which covers philosophical aspects of Bell’s theorem and entanglement, provides
this view, presented by Shimony as an acceptable physical interpretation (though not his favored view):

“Yes, something is communicated superluminally when measurements are made upon systems characterized by an entangled state, but that something is information, and there is no Relativistic locality principle which constrains its velocity.”

Fine [2] has pointed out that this distinction between thermodynamic and informational aspects, and the notion that information transmission is not constrained by the speed of light, can be traced to Bohr [7].

**Information transmission and its relation to physical states**

There are three aspects of this discussion I want to address. Firstly, what do we mean by information? This question extends to higher levels of philosophical discussion. For example, the quantum character of all physical entities has been invoked in a renaissance of Plato’s Forms, captured in the entangled states, as an explanatory basis for many of life’s mysteries, including the emergence of consciousness [16]. So the first point relates to information transmission. Shimony’s description begs the question of what is meant by “information” in this context. This question can be clarified by recognizing explicitly the difference between semantic and thermodynamic components involved in information transmission. As recognized by Shannon [17], the whole apparatus of Information Theory pertains to the “engineering aspects” of encoding and transmission, but says nothing about the semantic content or meaning of the message. This raises the question of the thermodynamic status of semantic content. I have argued elsewhere [18] that the value of semantic content is not measurable in thermodynamic terms, but only though translational processing in a specific context. Although the semantic content confers no additional thermodynamic burden, the message itself is only realized in the thermodynamic context of encoding, transmission (with a physical carrier), and of a transalational and interpretational machinery at the receiver end. If the semantic content has no thermodynamic status, it might be considered as unconstrained by superluminal considerations. However, all components of information transmission, - the several physical components of the engineering side, and the semantic content of the message, - are needed if communication is to be the result. The *something* in Shimony’s statement is constrained by relativity, unless information has an alternative meaning in which semantic content can be transferred without a thermodynamic vehicle. However, this would seem to open all sorts of possibilities for what my colleague Mike Weissman calls “science-fiction hell”. In line with this, the “impossibility of superluminal information transfer” has been suggested as “one of three fundamental information-theoretic constraints from which the basic kinematic features of a quantum description of physical systems can be derived” [19].

The second point is also philosophical. Bohr suggests that the “entire formalism is to be considered as a tool for deriving predictions”, and “functions like densities and currents are only to be regarded as expressing the probabilities”, appropriate for the status of the quantum mechanical account of the evolution of the quantum state as hypothesis. Like all hypotheses, it has a semantic component, and its epistemological status depends on how tightly this is tied to observation. Obviously, its *predictions* relate to the thermodynamic world, and these can be tested by measurement. However, the question of mechanism, of how to interpret the ontological
status of the wavefunction in terms of an intermediate state whose properties cannot be adequately determined by measurement, remains ambiguous. The limitations imposed by the uncertainty principle require a probabilistic treatment, divorced from direct measurement except in terms of the initial state and the outcome measurement. Bohr’s emphasis on “the measurement” was a recognition of the difference between these two aspects. In terms of entanglement, the evolution of the wavefunction is a probabilistic representation of our knowledge of possible outcomes arising from a transition in which complementary quantum objects are generated. The knowledge is derived from information about the initial state of the system and the characteristics of the transition, including properties that may include vectorial components such as polarization, orientation, and spin. The function is also an expression of ignorance (or uncertainty) as to the specific evolution of the entities, - which particular complementary properties are attributable to which entities. So long as the system is in this uncertain transitional state, it is necessary in QM to represent the evolution of the entangled entities by a single wavefunction defining probabilities for evolution starting from the initial transition, - the last tie to the phenomenal world. However, this is a philosophical, not a physical requirement; it does not seem required that one should assign a causal function to this description. The thermodynamic terms are modified by the probability term. But interpretation of the wavefunction as having some deterministic role seems to be at the root of much of the weirdness of quantum mechanical treatments. The extensive discussion about the “collapse of the wavefunction”, and the role of measurement, is predicated on some sort of thermodynamic reality for the wavefunction that seems to bring its behavior into conflict with superluminal limitations. But such states are, in Bohr’s expression, “…as is indicated already by the use of imaginary numbers,…not susceptible to pictorial interpretation”; they are mental constructs. The quantum objects are entangled because the treatment requires it. It is the ignorance that is resolved on interaction of one of the entities with a measuring device. Since the distance apart of detection systems in entanglement experiments can be arbitrarily extended, and the properties of the separated particles can in principle be detected simultaneously, any description in which the wavefunction of the entangled state is claimed to represent an energy distribution (as would be required in any causal interpretation) requires superluminal transfer of energy. If “information” is taken to involve semantic transmission, including a thermodynamic vehicle for semantic content, a superluminal exchange would also be implied. If superluminal exchange is forbidden, then we have to exclude these possibilities. On the other hand, if we accept the relativistic prohibition, the expectations can be established only by measurement, and a subsequent subluminal exchange of information. The “certainty” provided by the outcome measurement is initially local.

The third question relates to the point in the treatment of the entangled state at which QM is introduced. Entanglement experiments have shown that the expectations of the QM approach are accurately reflected in measurement of the complimentary entity, - the result anticipated in Bell’s inequality (cf. [20]). Since Bell’s theorem is taken to demonstrate “the incompatibility of local realistic theories with quantum mechanics” [15], it seems pertinent to ask just where QM comes into the treatment. Is it in the initiating transition or in the subsequent evolution of the “entangled” states? McHarris [21] has provided a succinct summary of the features of the QM that give rise to the difference between the classical and quantum mechanical approaches. The success of the QM approach comes from the use of Pauli spin matrices to set up the complementary properties of the entangled species; it is these that provide the upper limit of
Bell’s inequality ($2\sqrt{2} = 2.83$) that have been tested successfully in recent entanglement experiments [20]. But isn’t this treatment needed in description of the transition rather than the subsequent evolution? The use of Hilbert space to describe the evolution of the wavefunction is mathematically convenient, because it allows correlations between vectorial properties to be tracked and maintained in the context of a common wavefunction. However, couldn’t a more naïve view be justified? In any classical evolution of the “entangled” state in free space, correlation would be automatic because conservation laws would maintain correlations inherent in the initiating transition. Indeed, we would be worried if the conservation laws failed. The properties of any quantum object are determined by the transition generating it, and no not change (except for relativistic reasons) during a trajectory in free space. This is, after all, the principle on which our knowledge of the evolution of the cosmos is based. The success of QM in accounting for the evolution of the entangled states is directly related to its success in describing the transition, and in this sense is entirely local. There is no mystery to the subsequent evolution; the behavior can be ascribed to simple conservation laws. The objects are not entangled in any thermodynamic sense, - they are, in Einstein’s words. “spatially separate objects … independent of each other”.

An epistemological perspective

To the extent that the expectations of Bell’s theorem are met, quantum theory provides a “complete description” of our knowledge of possible outcomes in probabilistic terms [21, 22]. However, the need for a description of “entangled” states in terms of a common wavefunction is artificial, in the sense that it reflects concerns about the role of measurement in pinning down the uncertain epistemological and ontological status of the wave-like state. Confusion seems to arise only if the treatment is thought of as implying a thermodynamic linkage. Then all those “spooky actions at a distance” come into play, - and Einstein’s criticism can be seen as directed at this thermodynamic interpretation of the “$\psi$-function”. If we accept the wavefunction as probabilistic rather than thermodynamic, and the Hilbert space evolution as an accounting exercise, we do not introduce any philosophical conflict. We can state, while staying on firm epistemological ground that, although we do not have any mechanistic certainty as to what happens in the wavelike regime, we can predict the outcome with great accuracy if we understand the initiating transition. The treatment of the evolution of the “entangled” state through a common wavefunction is elegant but physically unnecessary and confusing, and the observed outcome can be predicted without “entanglement” from simple conservation considerations. There is no “collapse” of the wavefunction because the wavefunction does not have a thermodynamic role. There is, however, a resolution of uncertainty on identification of the location and orientation of a particular state of the system.

Although the treatment here relates to relatively simple systems, it should be obvious that for any set of entangled states generated through a single transition, the same sort of considerations will also apply. Although the wavefunction provides a convenient description, the treatment of the evolution through Hilbert space is unnecessary, and the outcome is dependent on conservation rules that are both more fundamental and simpler. If we accept this naïve view, we must also recognize that the great canopy of philosophical paradox erected over the entanglement question might be just so much fluff. This is not to be taken as an attack on quantum mechanics in general, - it is clearly necessary to consider in detail the interference
between wave-functions in many applications, and QM provides a successful analysis unavailable in the classical view. Nevertheless, speculations about such questions have introduced many different interpretations of quantum mechanics; all of these present epistemological and ontological paradoxes because of the role of measurement and the uncertainty consequent on Heisenberg’s considerations. These problems are especially acute in quantum mechanical treatments (and cosmological theories) that require postulation of other worlds inaccessible to our measurement, so that the constraints that have allowed quantum mechanics to claim its successes in our local universe no longer apply. This lack of access to measurement allows for expansion of speculation by some arbitrary power law, but the consequence is that proponents of such schemes are left skating on the thinnest of epistemological ice [23]. Since in some cases these excursions have their roots in discussion of entangled states, it might be possible to rein them in by asking if the entanglement has been disentangled from its philosophical underpinnings.

Acknowledgements
   I am grateful to Mike Weissman for an earlier criticism of this discussion, and for many important corrections, and to Martin Gruebele for insights into more general questions. Both might disagree with some of my conclusions, so I hasten to make clear that the above views, including any remaining errors, are entirely my responsibility (ARC).

References